Polarization of Inclusive Λ_c's in a Hybrid Model

Gary R. Goldstein [a*]

[a]Department of Physics, Tufts University
Medford, MA 02155

A hybrid model is presented for hyperon polarization that is based on perturbative QCD subprocesses and the recombination of polarized quarks with scalar diquarks. The updated hybrid model is applied to $p+p \to \Lambda + X$ and successfully reproduces the detailed kinematic dependence shown by the data. The hybrid model is extended to include pion beams and polarized Λ_c's. The resulting polarization is found to be in fair agreement with recent experiments. Predictions for the polarization dependence on x_F and p_T is given.

1. INTRODUCTION

Inclusively produced strange hyperons can have sizeable polarization [1] over a wide range of energies. Evidence now indicates that charmed hyperons also have sizeable polarization [2, 3]. Many theoretical models have been proposed to explain various aspects of hyperon polarization data with varying success [4, 5, 6]. All try to explain the large negative Λ polarization. Because the hyperon data is in the region of high CM energy but relatively small transverse momentum ($p_T \sim 1$ GeV/c), soft QCD effects should play a major role in any theoretical explanation. Several years ago Dharmaratna and Goldstein developed a hybrid model for Λ polarization in inclusive reactions [7]. The model involves hard scattering at the parton level, gluon fusion and light quark pair annihilation, to produce a polarized heavy quark which then undergoes a soft recombination that, in turn, enhances the polarization of the hyperon. This scheme provided an explanation for the characteristic kinematic dependences of the polarization in $p+p \to \Lambda + X$. The use of perturbative QCD to produce the initial polarization for strange quarks, with their low current or constituent quark mass (compared to Λ_{QCD}) made the application of perturbation theory marginal, however.

In the heavy quark realm the perturbative contribution is more reliable. Given these circumstances, I have modified the original hybrid model to apply to heavy flavor baryons produced inclusively from either proton or pion beams. The results are encouraging, as the following will show (see ref. [8] for a more complete treatment).

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2. HYBRID MODEL

All of the models for Λ polarization begin with the observation that Q-flavor hyperons of the type $\Lambda_Q \sim [ud]Q$ have their polarization carried primarily by the Q; the [ud] must be a color anti-triplet isospin 0 spin scalar diquark (to the extent that $gluons + \mathbf{L} + sea$ contributions can be ignored). How does the Q itself get polarized in a production process? Consider $parton + parton \to Q_\uparrow + \bar{Q}$. At tree level in QCD, there can be no single quark polarization for these two-body subprocesses, all diagrams being relatively real. This can be seen when the polarization is written in terms of helicity amplitudes $f_{a,b,c,d}$ for particles $A + B \to C + D$ as

$$\begin{aligned}\mathcal{P}_Q &\propto \sum_{a,b,d} f^*_{a,b;c,d} f_{a,b;c',d} (\sigma \cdot \hat{\mathbf{n}})_{c,c'} \\ &\propto Im \sum f_{a,b;+,d} f^*_{a,b;-,d}, \end{aligned} \quad (1)$$

where $\hat{\mathbf{n}}$ is the normal to the scattering plane. Hence there has to be a phase difference and a flip–non-flip interference. In QCD with zero quark masses there are only non-flip vertices; helicity flip requires non-zero quark masses. And a relative imaginary part only arises beyond tree level [9]. So the hybrid model incorporates the order α_s^2 QCD perturbative calculation of interference between tree level and the large number of one loop diagrams to produce massive heavy quark polarization. (Only the imaginary parts of the one loop diagrams were needed, so the Cutkosky rules were used to simplifiy the calculation. For the lengthy results see ref. [10, 11] as well as an independent calculation in ref. [12].) This gives rise to significant polarization [11], proportional to $\alpha_s(Q^2)$ and to complicated functions of the constituent quark mass. The

scale here is $Q^2 \sim m_Q^2 \gg \lambda_{QCD}^2$. The results are illustrated in fig. 1 for the $g + g \to Q_\uparrow + \bar{Q}$ case, with CM energy 26 GeV and outgoing quark flavors $Q = d, s, c, b$. The symmetry requires $\mathcal{P}(\pi - \theta) = -\mathcal{P}(\theta)$, so backward Q has $\mathcal{P} < 0$. The magnitude of $\mathcal{P}$ reaches $\sim 6\%$ for the b-quark. It is clear that the polarization increases roughly as the quark mass. Similar results are obtained for $q + \bar{q} \to Q_\uparrow + \bar{Q}$.

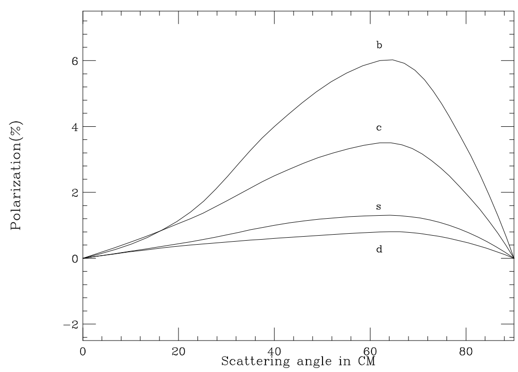

Figure 1. Polarization for the QCD subprocess of gluon fusion to quark pairs. The curves are for d, s, c, b quarks.

The cross sections for polarized Q-quarks (polarized normal to the production plane) must then be convoluted with the relevent structure functions for the hadronic beam and target. The inclusive cross section for *hadron* + *hadron* $\to Q(\uparrow \text{ or } \downarrow) + X$ is obtained thereby. For protons on protons gluon fusion is the more significant subprocess.

The hadronization process, by which the polarized Q recombines with a [ud] diquark system to form a Λ_Q, is crucial for understanding the subsequent hadron polarization. The backward moving, negatively polarized heavy quark must be accelerated to recombine with a fast moving diquark (resulting from remnants of the pp or πp collision) to form the hadron with particular x_F while preserving the quark's p_T value. Letting x_Q be the Feynman x for the heavy quark, the simple form, a linear mapping of the Q kinematic region,

$$x_F = a + b x_Q \tag{2}$$

is used for the recombination. Naively, if the Q has 1/3 of the final hyperon momentum (in its infinite momentum frame) and the diquark carries 2/3 of that momentum, then $a = 2/3$ and $b = 1$. The values actually used, $a = 0.86$ and $b = 0.70$, were chosen to fit the $pp \to \Lambda + X$ data (that existed in 1990) at one x_F value. These parameters in eqn. 2 are not far from the naive expectation.

This recombination prescription is similar to the semi-classical dynamical mechanism used in the "Thomas precession" model of hyperon polarization [5], which posits that the s-quark needs to be accelerated by a confining potential or via a "flux tube" [6] at an angle to its initial momentum in order to join with the diquark to form the hyperon. The skewed acceleration gives rise to a spin precession for the s-quark. With the precession rate, $\omega_\mathbf{T} = (\gamma - 1)\mathbf{v} \times \mathbf{a}/v^2 \propto \mathbf{p_Q} \times \mathbf{\Delta p_L} \sim -\hat{\mathbf{n}}$, an energy shift $-\mathbf{S} \cdot \omega_\mathbf{T} \propto +\mathbf{S} \cdot \hat{\mathbf{n}}$ occurs. Hence negative values of $\langle \mathbf{S} \cdot \hat{\mathbf{n}} \rangle$ are energetically favored. In the Hybrid Model the Q has acquired negative polarization already from the hard subprocess before it is accelerated in the hadronic recombination process. That "seed" polarization gets enhanced by a multiplicative factor $A \simeq 2\pi$ which simulates the Thomas precession. The Hybrid Model combines hard perturbative QCD with this simple model for non-perturbative recombination.

In summary, the hyperon polarization is given as

$$\mathcal{P}_{\Lambda_Q}(x_F, p_T) = A \cdot \mathcal{P}_Q(x_Q(x_F), p_T) \tag{3}$$

for each reaction $g(x_1) + g(x_2)$ or $q(x_1) + \bar{q}(x_2) \to Q\bar{Q}$, with the mapping function $x_Q(x_F)$ obtained by inverting eqn. 2. From eqn. 3 the subprocess polarized cross sections,

$$\frac{d^2\sigma(\uparrow \text{ and } \downarrow)_{i,j}}{dx_Q dp_T} \tag{4}$$

for partons (i, j) at (x_1, x_2) can be obtained. These cross sections are convoluted with the gluon, quark and antiquark structure functions for the proton and pion [13], $g^{p,\pi}(x), q^{p,\pi}(x), \bar{q}^{p,\pi}(x)$, or generically $f_i^{p,\pi}(x)$ leading to

$$\begin{aligned} \frac{d^2\sigma(\uparrow \text{ and } \downarrow)}{dx_Q dp_T} \quad &= \quad \sum_{i,j} \int_0^1 dx_1 \int_0^1 dx_2 f_i^{p,\pi}(x_1) \\ &\quad \cdot f_j^p(x_2) \frac{d^2\sigma(\uparrow \text{ and } \downarrow)_{i,j}}{dx_Q dp_T}. \end{aligned} \tag{5}$$

Next the recombination formula, eqn. 2, is applied to obtain the corresponding Λ_Q polarized

cross section at $x_F(= a + bx_Q)$ and p_T. The polarization is obtained via

$$\mathcal{P}_{\Lambda_Q}(x_F, p_T) = A \frac{d^2\sigma(\uparrow) - d^2\sigma(\downarrow)}{d^2\sigma(\uparrow) + d^2\sigma(\downarrow)}, \quad (6)$$

in an obvious notation.

Note that the linear form of eqn. 2 maps the Q-quark Feynman x region $[-1, (1-a)/b]$ into the x_F region $[(a-b), +1]$ for the Λ_Q. The $p+p \to Q$ differential cross section, $d^2\sigma/dx_Q dp_T$ is mapped correspondingly into the $p+p \to \Lambda_Q$ cross section $d^2\sigma/dx_F dp_T$. The measured cross sections for the latter are known to fall with positive x_F and to fall precipitously with p_T, roughly as

$$(1 - x_F)^{\alpha} e^{-\beta p_T^2} \quad (7)$$

overall [2], where α and β are greater than 1.0 (for $\pi + p \to \Lambda + X$ $\alpha, \beta \approx 3.0$). However, the directly computed lowest order p+p→s-quark cross section grows with x_Q in the region (-1,0) and it falls more gradually with p_T than the exponential in eqn. 7. Hence the more complete recombination scheme would have to temper the x_F dependence and narrow the p_T distribution. This will not affect the polarization calculation, though, since the individual up or down polarized cross sections will be alterred in the same way. For a more thorough calculation this should be done, and work is underway on this point. The polarization results are the focus of this work.

3. COMPARISON WITH DATA AND PREDICTIONS

Applied to strange Λ production, the hybrid model reproduces the detailed (x_F, p_T) dependence of the data, with very slow energy dependence [14], as fig. 2 shows.

Note that an estimated 20 to 30% of the Λ's come from $\Sigma^0 \to \gamma\Lambda$ [15], so the parameter A in eqn. 6 is increased to 7.9. The agreement of the hybrid model with the wide range of data is excellent.

It is worth remarking that recently extensive data have been collected on Λ polarization in many *exclusive* reactions [17], for which a simple form, $P = (-0.443 \pm 0.037)x_F p_T$, approximates all the polarization data at $p_{lab} = 27.5$ GeV/c. That form provides lower bracketing values for the inclusive polarization, as fig. 2 indicates. In the hybrid model all the final states other than the Λ arise from the hadronization of the $\bar{s}$-quark and the remains of the incoming baryons. Therefore, in the hybrid model it would be anticipated

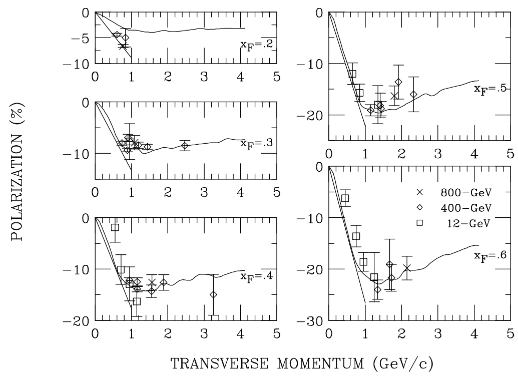

Figure 2. Hybrid model Λ polarization in $p+p \to \Lambda + X$ as a function of p_T for various values of x_F. The data at 12 GeV [14], 400 GeV [15], 800 GeV [16] are shown. Exclusive data at 27.5 GeV/c [17] is approximated by the straight line from the origin to $p_T \approx 1$ GeV/c.

that as the beam energy increases and/or more final states are included in the determination of the Λ polarization, more complicated final states will be accompanied by much lower polarization as p_T increases beyond 1 GeV/c.

In turning to Λ_c production, there is a straightforward scaling up that occurs in the $\mathcal{P}$ equations for $g + g$ and $q + \bar{q} \to c \uparrow + \bar{c}$. The seed polarization increases by ~ 3. The recombination with a fixed force/mass should have the same Thomas factor, but the overall recombination could scale as M_{hadron}, so a factor of $M_{\Lambda_c}/M_{\Lambda} \sim 2$ could apply. The scaled polarization in the reaction $\pi + p \to \Lambda_c \uparrow + X$ is obtained from the convolution of eqn. 5 with the π structure functions for the beam [13]. The predicted kinematic dependences for $\mathcal{P}(x_F, p_T)$ are shown in fig. 3 (without the hadron mass enhancement). Integrating over x_F from -0.2 to +0.6 allows the comparison with the data of E791 [3, 18], as fig. 4 shows. The lower curve has taken the additional factor of 2 that could apply to the scaling of the recombination. The higher curve does not have that factor and gives a poorer fit, albeit not far from the large uncertainties in the data points.

4. CONCLUSION

In conclusion, these results are encouraging for the hybrid model. The Thomas enhanced gluon fusion model has been modified to include quark-

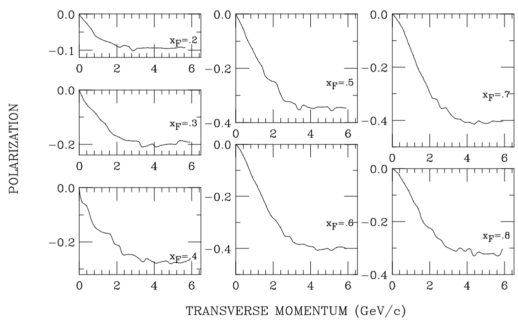

Figure 3. Λ_c polarization in $\pi^- + p \to \Lambda_c + X$ as a function of p_T for various values of x_F. Multipying these polarizations by $m(\Lambda_c)/m(\Lambda)$ will incorporate the hadron mass enhancements as in fig. 4.

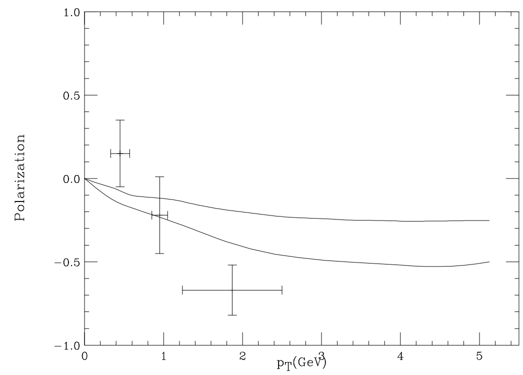

Figure 4. Estimate of Λ_c polarization from $\pi^- p \to \Lambda_c + X$. The larger polarization includes heavy mass enhancements. The preliminary data [3] is from E791.

anti-quark annihilation, which should be more prominent for heavy baryon polarization in pion induced reactions, like the above $\pi^- + p \to \Lambda_c + X$. Experimental data can be analyzed into x_F as well as p_T bins, so the predictions from the hybrid model can be checked in detail. It is important to realize that the results for the Λ_c were obtained without changing the parameters of the model that had been applied to the strange hyperons. Aside from the possible enhancement in A, everything else was simply scaled up by quark mass. This gives further credence to the results herein.

The somewhat *ad hoc* prescription for the recombination is being studied further in order to accommodate both the polarization and the cross section behavior of eqn. 7, with the kinematic variables x_F and p_T. The overall factor A may have some dependence on those variables as well, given that the semi-classical Thomas precession may have such dependence. Furthermore, an investigation of other hyperon production reactions, involving Σ, Σ_c, and Ξ, for example, is underway. Will $\bar{p} + p \to \Lambda + X$ carry significant, near energy independent polarization at collider energies? Can photoproduction of Λ produce large polarizations also? These can be answered within the hybrid model.

The related strange meson asymmetries in $p \uparrow + p \to K$ or π or Λ will be investigated in future work as well.

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